

Size Estimation with Night Vision Goggles

Anna Zalevski, James W. Meehan and
Philip K. Hughes

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Air Operations Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

Human observers matched the size of a comparison disc object to the perceived size of a test disc located at between 1 and 6 m under normal daylight viewing and when viewing through night vision goggles (NVGs) under simulated starlight. The results showed that observers were more accurate at judging size with unaided vision than when viewing with NVGs. The results for unaided viewing were in accord with the law of size constancy that predicts that accurate size estimation is a result of observers taking into account the distance at which objects are located. The results for viewing with NVGs depart from size constancy and are influenced to a greater extent by the law of visual angle that predicts that size estimates are based more on the angular size of the target because there is inadequate distance information available in this condition. These results demonstrate that NVGs alter normal visual space perception and this should be taken into account in training aircrew and evaluating the effect of NVGs on flying performance. Our results are consistent with other results reported in the literature for longer observation distances.

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Size Estimation with Night Vision Goggles

Executive Summary

Night vision goggles (NVGs) are electro-optical devices that use image intensifiers to amplify ambient near infrared light so that objects can be seen under reduced illumination conditions. NVGs enable visually guided tasks such as low level helicopter flight to be performed more safely at night.

The appearance of scenes in NVGs is altered compared with normal daytime viewing so that the visual cues humans normally rely on are impoverished when viewed through NVGs. For example, the field of view is limited to 40 deg, the visibility of high spatial frequencies is reduced, images are monochrome, reflectance and contrast of objects differ to their appearance with normal vision, and visual noise and scintillation are visible in the image. An experiment was conducted to determine the effects of using NVGs to estimate the size of target objects compared to size estimates made with unaided vision under high illumination conditions. A modified version of Holway and Boring's (1941) corridor experiment was conducted with a disc size-matching task over distances of 1 to 6 m.

The results showed that observers were more accurate at judging size under high illumination conditions with unaided vision compared to viewing with NVGs under simulated starlight illumination. The results for unaided viewing are in accord with the law of size constancy that predicts that accurate size estimation is a result of observers taking into account the distance at which objects are located. The results with NVGs depart from size constancy and are influenced to a greater extent by the law of visual angle that predicts that size estimates are based more on the angular size of the target because there is inadequate distance information available in this condition. Our results are consistent with other results reported in the literature for longer observation distances.

These findings provide a basis for understanding the likely impact of NVGs on human performance in visually directed tasks that depend upon correct judgments of object size and distance at night while wearing NVGs.

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1. Introduction

Following the mid-air collision of two Army Black Hawk helicopters in June 1996, the Board of Inquiry (O'Sullivan, Jones, Pascoe, and Ellis, 1996) concluded that one of the sixteen causes of the accident was "a failure to make proper allowance for the known characteristics and limitations of NVG" (pp. 4-12). Although the Board of Inquiry identified many other causes and contributory factors, there is nevertheless widespread appreciation that the ability of aircrew to perceive their visual environment accurately through night vision goggles (NVGs) is a critical flight safety issue and a determinant of overall mission success.

NVGs are electro-optical devices that enhance visibility in low light. Vision with NVGs differs in many ways from unaided human vision. This report explores one aspect of vision through NVGs, that is, how perception of the size of objects differs when viewed through NVGs compared with perception of the same objects viewed normally. Other aspects of the characteristics and limitations of NVGs are reported elsewhere.

The purpose of the work reported here is to advance understanding of the impact of the world viewed through NVGs on human visual performance. The strategy adopted was to evaluate the effect on performance of a representational and highly salient visual task that invoked spatial perception. The reason for this is that NVGs have been introduced into military service because they allow the performance of operational tasks at night that could not be performed otherwise, and these operations depend on the ability of NVGs to provide spatial perception at night.

2. Background

2.1 Visual Space Perception

Visual space perception can be thought of as the ability of humans to perceive the spatial layout of objects and surfaces in the visual world. It is usually effortless, but is a complex skill that enables safe navigation through the physical environment by enabling the detection and recognition of the direction and location of objects in relation to the viewer or to each other. It also permits the perception of absolute and relative size and distance of objects using a variety of visual cues. These judgments are performed by humans constantly when stationary and in the more complex situation where an observer moves through the visual world that contains objects that are both fixed and moving.

Under normal viewing conditions humans are reasonably accurate in judging the direction, distance, and size of objects and in manoeuvring themselves or vehicles under their control around the environment. Under degraded visual conditions due to adverse weather or when light levels fall, errors can occur in spatial judgments. The visual environment can also be degraded when seen through viewing devices. For example, telescopes, periscopes, binoculars, and NVGs all greatly restrict the field of view thereby obscuring the peripheral visual field, and images from remote video cameras and sensors presented on a raster display lose some fine detail. Factors such as these can reduce the informational content of a visual scene compared with direct viewing under clear, well-lighted ambient conditions. It is therefore important to understand the likely impact of a viewing device on the visual performance of the user, particularly in depth perception. Essential characteristics in the visual perception of depth of

objects are size and distance, which are linked. Although an observer may not explicitly estimate the size or distance of a viewed object in physical units, some internal transformation of this must be used by cognitive processes in order to make meaning of the physical world.

2.2 Spatial Perception Tasks of Aircrrew

Helicopter pilots frequently need to make accurate estimates of the size of objects and terrain features. For example, judgments of the size or height of trees is important during low flying, especially nap-of-the-earth flight. Pilots need to estimate the size of landing pads from a distance to judge whether a safe landing is possible. Safe hover and manoeuvres in confined areas require pilots to estimate the size, and therefore encroachment, of trees, vehicles, and any other natural or artificial objects close to the aircraft. The size of other aircraft needs to be known to allow safe manoeuvring and to maintain safe separation during formation flight. Pilots may not always explicitly or consciously estimate the size of objects, but object size is an important aspect of accurate spatial perception. Clearly, pilots do not solely rely on their perceptual and cognitive judgments of size, distance, and direction, but will also take into account information from navigation and targeting sensors that provide similar kinds of distance information, as well as verbal communications from other aircraft and ground personnel. However, in most circumstances pilots will rely primarily on what they normally perceive in the visual world.

2.3 Normal Size Perception

2.3.1 Visual size constancy

Although it is established that a single cue can give rise to a particular perceptual phenomenon, under most operational conditions, numerous cues are involved. For the most part, cues for perceived size mediate perception of the world that is stable, constant, and veridical, that is, true size, shape and relative positions of objects in space are maintained under most normal viewing conditions, regardless of the orientation or distance of the observer from the objects viewed. This stable view of the world is generally referred to as *visual constancy* (eg, Hochberg, 1972).

It is sometimes assumed that the perceived size of an object is based on its subtended angular size at an observer's retina. The distance of an object and its actual size both influence its perceived size. The law of visual angle would predict that an estimate of an object's size will be based solely on its subtended visual angle. However, the perceived size of objects can be shown to depend not only on the size of the image that it projects at the retina, but also on the proximal cues for its distance (Holway and Boring, 1941).

The image that an object of a given size at a fixed distance projects on to the retina will always remain constant. When the viewing distance of the object is reduced, its retinal image increases, but it tends not to be perceived as larger. For example, a 9 m tree viewed from 15 m distance will seem approximately the same size as when viewed from 30 m, despite it subtending only half the visual angle. The observer's visual experience is that the tree is not half as tall at the farther distance, but approximately the same. At each distance, the tree appears more or less the same size; perception of nearly constant size is preserved with large differences in retinal image size.

2.3.2 Distance cues

There is evidence to suggest that observers take into account an object's distance when scaling its perceived size (eg, Rock, 1975). Gillam (1995), however, argued that size is also determined by contextual factors such as the location of objects in reference to the horizon and other objects, but it could be argued that the spatial relationships of objects also comprise cues for distance. A more general statement of this is that the perception of spatial depth is not usually evoked by a single cue, but is an outcome of multiple cues available in a visual scene (Cutting, 1997; Meehan and Day, 1995).

Cues for distance can be monocular and binocular. Monocular cues are those that provide similar information whether viewed by one or both eyes, whereas binocular cues depend on the viewer having two normally functioning eyes.

There are various types of monocular cues. Interposition (overlap) is the overlap of objects at different egocentric distances along the line of regard. This results in partial obscuration of a distant object by another, indicating that the object which is partially obscured is more distant than the object that obscures it. Perspective cues include the apparent convergence of parallel lines as they recede (geometric perspective) and texture gradient, the apparent decrease in the size and spacing of textural elements with distance. Aerial perspective changes the appearance of objects in scenes as distance increases, with the objects in the distance seen less distinctly than those closer to the observer. Spectral shift also results in very distant scenes appearing more bluish than near scenes. Elevation or position in the field relative to the horizon can also indicate distance, with objects higher and closer to the horizon appearing to be farther. Motion parallax (see Rogers and Graham, 1979) refers to the appearance of closer objects moving more rapidly in the optic flow field of a moving observer compared to the relatively slow angular velocities of more distant objects and terrain.

Binocular cues arise from the independent views of the world seen by each eye. Stereopsis arises from object contours stimulating non-corresponding retinal points in the two eyes resulting in binocular disparity and the perception of relative depth between the contour and the point of fixation. Stereopsis is a cue for depth that is useful practically up to distances of about 30 m. The action of convergence of the two eyes potentially provides information about the distance of a fixated object, but the effectiveness of this is greatly diminished for distances beyond about 6 m (Wallach and Floor, 1971).

In addition to stereopsis, the state of accommodation to objects of varying distance may also yield information about distance, but it is unlikely accommodation contributes to perception of size for objects beyond about 1 m (Leibowitz and Moore, 1966).

2.3.3 Empirical studies of size constancy

Empirical evidence from different experimental paradigms has verified constancy in observers' perception of size. Size constancy has been demonstrated in indoor and natural outdoor settings and also in virtual environments.

Holway and Boring (1941) seated observers at the intersection of two corridors and asked them to match the apparent size of a test disc by adjusting the size of a comparison disc, each projected on a white screen in one of the corridors. The test disc was placed in one corridor at different distances ranging from 3.1 to 36.3 m from the observer. Each test disc was selected so

that at its viewed distance it always subtended 1 deg of visual angle in order to maintain a constant retinal image size. The adjustable comparison disc was presented in the second hallway, always at 3.1 m. On each test disc presentation, the observer was asked to compare and match the size of the comparison disc to that of the test disc. The size of the comparison disc was continuously varied by the experimenter until the observer was satisfied that the two stimuli appeared the same size. This procedure was carried out under different combinations of conditions.

Holway and Boring manipulated the visual depth cues available to the observers with binocular viewing, monocular viewing, and monocular with an artificial pupil. They also degraded viewing conditions systematically by reducing the amount of ambient light and contextual information visible in the corridor. They found that size constancy was generally maintained in the presence of adequate distance information but, as distance information was progressively degraded, perceived size of the test disc shifted towards that which would be determined by its visual angle alone. Their results suggest that observers can judge the size of an unfamiliar object accurately only to the extent that they have reliable cues about its distance. In the extreme case of complete elimination of context and distance cues, Lichten and Lurie (1950) showed that judgment of size became based solely on visual angle.

2.3.4 Size estimation outdoors

Even at extreme distances outdoors, size constancy does not break down completely when adequate cues for depth perception are available. This was shown by Gibson (1950) in an open-field experiment in which target stakes varying in length were placed at different distances in a half-mile long field. The task of observers was to choose a comparison stake that appeared to be the same size as the target stake nominated at random by the experimenter. Variability of the estimates increased at the longest distances, but mean estimates indicated that size constancy was generally maintained out to a distance of 716.9 m.

Gilinsky (1955) applied Holway and Boring's paradigm outdoors over greater distances than Gibson that ranged from 15.24 to 1219.20 m. The targets she used were isosceles triangles of equal base and height that ranged in height from 1.06 to 1.98 m. The "standard" target was placed randomly at one of six distances that varied from 30 to 1200 m. Unlike Holway and Boring, Gilinsky did not make visual angle of the targets located at each distance the same. For each target distance, observers adjusted the size of a variable comparison triangle, placed 36 deg 26 min to the right, so that it appeared approximately the same size as the standard. The comparison triangle was fixed at 30 m distance, and its size was adjusted remotely by the observer.

Gilinsky used two different instructions to observers. In the first "objective" condition, observers were asked to judge size in terms of the absolute or physical size of the targets and to imagine their size measured with a ruler in order to assess equality. In the second "retinal" condition, the emphasis was for observers to superimpose the memory of the image of one target on the other in order to assess equality. This emphasised the retinal angle of the targets, and the results were in between those based on visual angle alone and size constancy. In the first condition, mean judgments represented over-constancy. Gilinsky argued that this overestimation was the normal perceptual outcome consistent with size constancy, and was a result of the effects of the outdoor environment providing natural depth cues for the observer. It is interesting to note that although the order in which each condition was counterbalanced, all observers performed

under both, so it cannot be ruled out that performance under one condition influenced the other.

2.3.5 Size estimation in artificial environments

Experimentation with size constancy has not been restricted to physical objects. Howard (1996) replicated Gilinsky's (1955) size-estimation experiment in two different aircraft simulators with the same target sizes and distances. This was achieved by reproducing the outdoor environment used by Gilinsky in the simulator terrain data base. The observers in Howard's experiment overestimated the angular size of the standard triangle (see Figure 2, Section 4 below), however, the degree of overestimation was less than in Gilinsky's study, ranging from approximately equal matches at a simulated distance of 30 m to 1.6 times at a simulated distance of 1219 m. Howard argued that this smaller degree of overestimation was a result of the reduced depth and distance cues available in the simulator compared to those available in the real outdoor environment. This suggests that accuracy of size estimates would be promoted by the instatement of as many depth cues as possible in a simulator, and possibly by augmenting synthetic scenes with additional cues for depth.

Palmer and Petitt (1977) replicated the essential experimental protocol of Holway and Boring (1941) in an aircraft simulator in order to determine whether collimated or non-collimated imaging optics or scene augmentation (objects inserted to increase scene detail) influenced size judgments. Interestingly, in this experiment the observers overestimated the angular size of targets to a greater extent with collimated imagery than with the inferior non-collimated optics (Figure 2, Section 4 below). However, this particular finding would need to be interpreted cautiously, as numerous aspects of virtual environments used in simulators differ from normal human visual experience (for discussion, see Meehan, 1996).

If the visual scene is degraded compared to natural viewing conditions, the perceived size of objects shifts away from constancy in the direction of their visual angle. This outcome was found by Eggleston, Janson, and Aldrich (1996) who essentially repeated the experiment of Holway and Boring (1941) in a helmet mounted display (HMD) manipulating some of the display's characteristics. They found that size judgments were based on the visual angle of the target for both binocular (the same image presented to both eyes simultaneously) and stereoscopic imagery, for high and low resolution imagery, for 100 and 60-deg fields of view, and for different levels of target and background contrast. Eggleston et al argued that the optical arrangement of the HMD may have altered the relationship between visual accommodation and convergence, possibly disrupting spatial perception. Moreover, it can be observed that the schematic depiction of simple geometric objects that they used is not the same as viewing three-dimensional physical objects in the real world, and therefore the conditions of normal space perception were not present, so it is not surprising that size judgments failed to reflect constancy.

In summary, when many cues for depth and distance are available, observers tend to base size estimates on the actual sizes of stimuli as predicted by size constancy. When cues for depth are reduced or eliminated, for example by viewing through an artificial pupil, viewing with one eye, or by degrading the visual display system in some other way, then size estimates depart from size constancy and judgments tend to reflect more reliance on visual angle of the stimulus. Elimination of all depth cues results in size judgments based on visual angle alone.

2.4 Size Perception with Night Vision Goggles

2.4.1 Characteristics of night vision goggles

Spatial perception and discrete aspects of it such as judgments of size are mediated by an array of visual cues that may be more or less available to the observer depending on viewing conditions. Viewing with NVGs affects or reduces numerous cues for depth upon which accurate judgments of object size depend. This is not to deny that NVGs have introduced a considerable improvement in operational performance during night-time missions, rather, the imagery that NVGs provide differs from unaided vision in several ways that may contribute to altered space perception compared to unaided viewing, and there is a need to understand this.

The stereopsis threshold with NVG viewing is about four times greater than with normal viewing. The normal unaided threshold is approximately 5 arcsec disparity, whereas with NVGs this is increased to 20 arcsec (Knight, Apsey, Jackson, and Dennis, 1998). Although stereopsis may not provide useful information for depth at long distances, it is nonetheless a fundamental attribute of normal vision that is adversely affected when viewing with NVGs. Thresholds for visual acuity and contrast are also elevated compared with unaided vision (Rabin, 1993), and similarly, these are basic visual functions that are fundamental to visual space perception.

The restricted instantaneous visual field of approximately 40 deg limits the ability of an observer to integrate and compare different areas of the visual scene. It might therefore be expected that head movement behaviour will be altered when viewing with NVGs because more scanning of the visual scene will be required to sample the scene than with normal viewing (Wells and Venturino, 1990). It has been suggested that this change could induce disorientation (Dolezal, 1982), and possibly distort space perception (Kraft and Green, 1989).

The characteristic noise and scintillation effects of NVGs are not normally experienced with unaided vision. Similarly, monochromatic vision is not the normal experience of unaided vision. However, the effects of these factors on space perception have not been fully investigated, although these factors do degrade target detection and form perception (Uttal, Baruch, and Allen, 1994).

The dissimilar spectral sensitivity of NVGs (approximately 625 to 930 nm) compared to normal vision (approximately 380 to 780 nm) combined with different spectral reflectivity in these bandwidths results in some objects having a different appearance with NVGs compared to unaided vision. The relatively bright appearance of vegetation is due to the higher reflectance of near infra-red wavelengths compared to reflection of visible light. The way this affects contrast and texture perception and ultimately visual space perception is not well understood.

All these factors contribute to an altered NVG image compared with normal unaided vision under photopic conditions. What is less certain, however, is how aspects of higher-order visual performance such as form, motion, and space perception are affected by NVG imagery, and in turn, the effect of these factors on operational flying tasks that rely on complex visual and cognitive input. Although the precise role of contributing factors remains uncertain, there is sufficient operational and anecdotal evidence to conclude that NVGs are associated with errors in the estimation of depth, altitude, distance, and size (Fuson, 1990).

2.4.2 Perception of size

Although there have been studies of distance estimation through NVGs, no studies to date have been reported that have explicitly investigated estimations of the size of objects viewed with NVGs, except in simulation. In an experiment conducted in a flight simulator, Howard (1996) required observers to make size estimates. The estimates were made in the simulator under normal viewing conditions, and with NVGs and reduced display luminance. Observers overestimated the angular size of triangles in both conditions, but did so to a greater extent under the unaided viewing condition (1.62 times at the longest observation distance of 1219 m) compared with NVG viewing (1.38 times). Judgments with NVGs resulted in judgments more in accord with the law of visual angle than the law of size constancy. This finding indicates that cues for size available in imagery projected on a dome display are reduced when viewing through NVGs. Furthermore, the size estimates obtained in the dome were smaller than those obtained in the open by Gilinsky (1955) (overestimation ratio of 1.4 compared with 3.9), which indicates that cues for object size are reduced in a simulator and with NVGs compared with normal viewing in the natural environment.

2.4.3 Spatial disorientation with night vision goggles

There are many anecdotal accounts of helicopter pilots making errors in space perception that may have lead to incidents and accidents. Although size perception has not always been identified specifically as a contributory factor, it is likely that errors of space perception (such as object distance and clearance estimation, and perception of closure rate) include size perception as a component factor. Spatial disorientation is an aspect of degraded space perception that is a recognised contributory factor to many rotary-wing accidents. Benson (1988) defined spatial disorientation as occurring "...when the aviator fails to sense correctly the position, motion, or attitude of his aircraft" (p. 277). Although the causes are complex and not always evident, maintenance of spatial awareness will tend to depend on visual perception of self-motion and the size, distance, shape, and orientation of objects and surfaces in the physical world.

Braithwaite, Durnford, Crowley, Rosado, and Albano (1998) surveyed all US Army Class A to C rotary-wing accidents in the period 1989 to 1995 and found that spatial disorientation was implicated in 30% of accidents. Of these, the accident rate for flight with Night Vision Devices (NVDs), both NVG and forward-looking infrared (FLIR), was 9.99 per 100,000 flying hours, compared with 3.87 for unaided night flight and 1.66 during the day (Braithwaite, Douglass, Durnford, and Lucas, 1998). The visual limitations of NVDs were implicated in 29% of night accidents, misjudgments of clearance from obstacles was involved in 84% of accidents, and 23% of accidents involved insufficient visual cues. NVGs were used in 33% of all accidents in which spatial disorientation was a factor (Braithwaite, Douglass, et al. 1998). It is important to note that experienced and inexperienced aircrew were equally represented in spatial disorientation accidents involving NVDs. Braithwaite, Douglass, et al. (1998) suggested that the most important factors in accidents where NVGs were used were insufficient illumination and poor environmental visibility (such as with low contrast terrain), but that visual illusions with NVGs occurred infrequently.

Crowley (1991) obtained written responses from 212 rotary-wing aircrew on their experiences of sensory effects and illusions when using NVGs. Although size perception was not explicitly mentioned in the open-ended questionnaire, 16% of respondents reported difficulty with height judgments, 11% reported impaired depth perception, and 6% reported faulty closure judgment

when using NVGs. The illumination existing when these misjudgments occurred was usually below quarter moon (61% of incidents). These survey results point to the importance of having adequate visual information for safe rotary-wing operations, and that use of NVGs is frequently represented in incidents involving errors in spatial perception.

2.5 Distance Perception

The relation between size and distance aspects of space perception led Gibson (1950) to conclude "There is no such thing as an impression of size apart from an impression of distance" (p. 186). Presumably, accurate size judgments are possible only when there are adequate cues for the distance of an object and accurate distance judgments are facilitated by knowledge of the size of objects.

The size-distance invariance hypothesis as described by Kilpatrick and Ittelson (1953) states that the visual angle of an object is proportional to its perceived size and inversely proportional to its perceived distance. As an object recedes, its visual angle necessarily decreases, but to judge its size correctly at any distance, an observer will need to take distance into consideration. Realising that space perception is unlikely to be based solely on the geometric relationships, Kilpatrick and Ittelson (1953) distinguished the physical relationship between visual angle, size, and distance, and the psychological relationship between perceived size and distance, and subtended visual angle. Acknowledging that physical size and distance have a simple geometric relationship, Kilpatrick and Ittelson cautioned against assuming the relationship applies equally in the psychological domain. For example, Meehan and Triggs (1988) showed that when natural scenes are viewed through an imaging display of unity magnification, there is a reduction in their apparent size, and apparent size and apparent distance are not always influenced uniformly by the informational content of natural outdoor scenes (Meehan and Triggs, 1992).

Day and Parks (1989) also suggested that the relationship between perceived size and perceived distance is not always symmetrical, but nonetheless the perceptions of size and distance are interdependent in that they both usually involve common cues. They stated that "...perceived size, like perceived distance, is determined by numerous cues. Distance might serve as one cue to size and, similarly, size might serve as one cue to distance. Depending on the conditions of viewing, other cues to both these dimensions might come into play" (p. 349).

Information about the size of objects, where such information can act as cues for distance, can take various forms. Ittelson (1951) showed that familiarity with object size is an effective cue for distance. The relative size of objects, for example, can indicate how far away from the observer they might be located. Ittelson also showed that when similar objects are viewed at the same distance, the smaller of the two will appear further away. This arrangement replicates at the retina the proximal conditions that prevail if the two stimuli are the same size, but one is further away. However, it can be noted that this relationship sometimes breaks down at large distances, or under unusual viewing conditions (Woodworth and Schlosberg, 1954, p. 480-486).

2.5.1 Size-distance estimation in natural scenes

Gilinsky (1951) showed that the size-distance invariance principle does not always hold so that although distance constancy is preserved at short distances, this relationship may break down at longer distances where distances are underestimated compared to near ones. In one of her experiments, the task of the observers, who stood at one end of a 28 m long archery range, was

to direct the experimenter in marking off successive increments of equal perceived length (eg, 1 m steps). The results indicated an underestimation of distance so that a perceived distance of 10 m corresponded with a physical distance of 15.3 m (65%), and a perceived distance of 14 m corresponded with a physical distance of 28 m (50%). The perceived 1 m intervals became subjectively larger with increasing distance so that what was perceived as 1 m was equivalent to a physical distance of 2.2 m at 10 m and 4.4 m at 28 m distance. The observers tended to underestimate absolute distances and the amount of underestimation increased with observation distance.

Contrary to these findings, Higashiyama and Shimono (1994) found a close relationship between perceived and physical estimates of size and distance, but that the variability of estimates increased at long distances of a few kilometres. Although both size and distance estimates, if made with natural vision and in the presence of natural distance and size cues, can be reasonably accurate even at large distances, the extent of the ground plane may affect judgments leading to underestimation or overestimation of distance. For example, Galanter and Galanter (1973) found that observers overestimated the distance to low-flying aircraft but underestimated distances to aircraft flying overhead.

It is likely that any disruption to distance perception probably also affects size perception because an observer must take into account variations in both an object's angular size and distance according to the size-distance invariance relationship if accurate judgments of perceived size are to be made. Hence, the task of the observer may itself influence the accuracy or otherwise of the judgment being made.

2.5.2 Size-distance estimation with night vision goggles

The few studies to investigate distance estimation performance with NVGs give variable results that are difficult to generalise to the range of operational conditions in which aircrew must make spatial estimations. While there is some evidence that individuals can be predisposed to overestimate or underestimate object distance when using NVGs, distance misjudgments have nonetheless been regarded as one of the factors responsible for rotary-wing accidents during night-time missions (Fuson, 1990).

Foyle and Kaiser (1991) conducted a field study of absolute judgments to targets located between 6.1 and 60.1 m. Measurements were made during the day with unaided vision and at night with ANVIS 6 NVGs by four helicopter pilots with extensive NVG experience. All observers underestimated the distance to the target using unaided viewing with either their normal or a restricted field of view, but during NVG viewing two observers overestimated and two observers underestimated distance. The restricted field of view of NVGs was therefore not the primary cause of underestimation of distance but the interaction between field of view and resolution with NVGs appears to result in variable performance between individuals.

However, in a laboratory study DeLucia and Task (1995) found that observers typically underestimated distance judgments when using ANVIS 6 NVGs. For example, for observation distances between 6.6 and 13.1 m, observers perceived a terrain board object to be about 22% closer than its physical distance using NVGs compared to 14% closer with unaided vision. Observers also perceived the bisection or midpoint between themselves and the target to be closer than it was which also suggests they underestimated physical distance. However, performance was similar for NVG and unaided viewing conditions. When moving towards an object, observers stopped further away from it to avoid colliding with it when using NVGs (0.87

m) compared to unaided vision (0.52 m), which suggests the target was perceived to be closer than its physical location.

Hadani (1991) has also reported that observers underestimated the distance to an object and proposed that altered space perception with NVGs is due to the forwardly displaced location of the nodal point of the objective lens of NVGs compared with the nodal point of the eye which is located inside the eye. This difference in perspective due to the physical location of the objective lens approximately 15 cm in front of the eyes affects space perception despite NVGs having unity magnification but is probably more noticeable at distances of a few metres compared to longer distances.

Many distance estimation tasks have been conducted in laboratory settings with simple tasks that may not be representative of perceptual judgment required of aircrew. DeLucia and Task (1995) compared judgments in the laboratory and in a field experiment. In the laboratory, they found that wearing NVGs, observers underestimated distance compared with normal photopic viewing. In an outdoor experiment in a motor vehicle, observers were asked to judge distance by indicating when they would initiate a turn to avoid colliding with a target they were approaching. It was argued that this task was more valid ecologically. In contrast with the laboratory experiment, they found no significant differences between NVG and unaided viewing. This discrepancy has not been resolved. It could be that task specific factors such as type of NVGs, vehicle speeds involved, task complexity, type of objects in view, and possibly other unknown factors influenced the estimates made by the observers in each experiment.

In another field study, Reising and Martin (1995) had observers make estimates of absolute depth between themselves and triangular targets, and make depth judgments between pairs of targets under starlight conditions following a period of familiarisation with the targets and distances involved. Of the 20 observers participating, 14 underestimated the absolute distance to targets located between 8.5 and 41.2 m, and two observers overestimated distances. However, there was no bias in estimates of distances between targets within the same range of distances as the absolute measures. There was a significant improvement in distance estimates when observers had previous knowledge of the distances involved and feedback of their performance during a training session. Niall, Reising, and Martin (1997, 1999) confirmed the value of direct verbal feedback for distance estimation when viewing through NVGs. They also showed that observers typically underestimated the true physical distance only if they had limited experience using NVGs and had no feedback on their performance.

Although NVG images were not used, Roumes, Meehan, Plantier and Menu (1992) videotaped circular targets in a field outdoors over extended distances and presented the videotaped images to observers in the laboratory under three binocular conditions: stereo with crossed disparities, stereo with uncrossed disparities, and biocular. Targets were videotaped at four distances: 20, 40, 80, and 160 m. Overall, typical underconstancy was observed for the longest distance, whereas estimates were accurate for the two intermediate distances. Underconstancy was also observed for the closest distance, and this was attributed to an artefact of the method. When expressed as a power function, the stereo-uncrossed disparity condition was found to produce more accurate estimates than the other two conditions. While this study did not emulate night vision conditions, it points to another source of potential influence in judgments of distance with synthesised images of real-world scenes. It should be recognised that NVG images do not present a direct view of the world as do binoculars, but rather a transduced image via the image intensifiers.

In summary, distance judgments are typically underestimates when viewing through NVGs so that objects appear closer than they really are, but inter-observer differences and training, as well as the specific task and viewing conditions, may determine whether distances to objects are underestimated or overestimated.

2.6 Present Study

The present study was directed to understanding the influence of NVG wearing on human spatial perception. The specific aspect of spatial perception to be investigated was object size estimation. This was selected because of its direct influence on overall spatial judgments and also because there were no reports of previous research in size judgments with NVGs. A partial replication of the size estimation task of Holway and Boring (1941) was adopted, as this provided a robust paradigm. It was expected that estimations of object size would be less accurate when viewed with NVGs compared to unaided vision under photopic levels of illumination, and that estimates might be less accurate at longer viewing distances.

3. Method

3.1 Observers

Eight observers (6 male and 2 female) aged between 24 and 35 years volunteered for the experiment. All had normal or corrected-to-normal binocular vision of Snellen 6/6 tested with a logMAR chart (Bailey and Lovie, 1976). All observers were scientific staff employed within DSTO and none had previous experience with NVGs.

3.2 Apparatus

The six target test stimuli were white plastic discs having a diameter of 1.8, 3.5, 5.3, 7.0, 8.7, or 10.5 cm. These sizes were selected so that each subtended 1 deg of visual angle at its viewed distance. In addition, there were 19 comparison discs ranging in diameter between 1.2 and 11.6 cm in steps of approximately 0.5 cm. Comparison and test discs were placed on black metal stands in front of a black cloth background 1.2 m wide and 1.5 m high. The height of the stands was adjustable in order to match each observer's eye height when seated.

The experiment was conducted in a light-proof laboratory, the walls painted light grey, and the floor covered with grey carpet. The disc luminance in the normal photopic viewing condition was approximately 80 cd/m^2 , with discs illuminated from the ceiling by 18 incandescent globes. The discs in the NVG viewing condition were diffusely illuminated by a Hoffman LM-33-80A Night Sky Projector (colour temperature 2856K) which was pointed toward the rear wall. The average disc luminance was $1.74 \times 10^{-4} \text{ cd/m}^2$ corresponding to a night vision imaging system (NVIS) radiance of $1.29 \times 10^{-10} \text{ NR}_A$. The average luminance of comparison discs was $1.69 \times 10^{-4} \text{ cd/m}^2$, equivalent to $1.24 \times 10^{-10} \text{ NR}_A$. Under these stimulus conditions, the NVGs were operating with a gain equivalent to that under starlight illumination.

The NVGs used were model F4949 (Serial number 4091) manufactured by ITT Defense and Electronics, fitted with Omnibus 4 image-intensifier tubes.

3.3 Procedure

The test disc was presented at either 1, 2, 3, 4, 5, or 6 m in front of the observer and each comparison disc was placed at 90 deg to the right of the observer at a constant distance of 2 m so that the test and comparison discs could not be viewed simultaneously. Each test disc subtended 1 deg visual angle and the order of presentation of test discs was randomised. On each trial the observer's task was to match the size of the comparison disc to that of the test disc. The size of the comparison disc was changed from a randomly chosen initial size according to the method of limits by the experimenter displaying discs of different sizes in either an ascending or descending order until the observer indicated that the comparison disc and target disc were equal in size. While the experimenter was changing the comparison discs, the observer was required to fixate the test disc. As the comparison disc was 90 deg away from the test disc, the observer was required to turn away from the test disc by about 45 deg to see the comparison disc, which ensured that the match was on the basis of recalled size rather than the actual size of the comparison disc¹.

The observers were instructed in correct NVG adjustment and focusing procedures, and they were instructed to focus their goggles using a white 8.7 cm disc provided for this that was located at a distance of 5 m. The observer was encouraged to spend as much time as required to adjust and focus the goggles prior to commencement of the experiment.

The experiment was conducted in two sessions. The first session, which lasted approximately 45 min, involved size matching with unaided binocular vision under photopic illumination conditions, and comprised four size-matching estimates for each of six distances, with two ascending and two descending trials. The second session, which took place after a break of about 20 min, and which took approximately 1.5 h, involved viewing with NVGs using the same procedure.

There was no time limit, and the observers were free to look back and forth between the comparison and test discs as often as necessary before making a decision about the disc size in each trial. The study therefore comprised six target distances and two viewing conditions in a within-observers randomised-block factorial design. Each disc size judgment was replicated four times at each of the six observation distances for both viewing conditions.

4. Results

Table 1 gives the actual test disc diameters and the mean dimension of the comparison disc (in physical and angular diameter) selected to match the 1-deg target disc. This dimension denotes the perceived size of the test stimulus at each of the six distances. The results show that as viewing distance increased, observers made increasingly larger estimates of the target size that reflected the actual size of the target disc, but this was less so for the NVG condition, where estimates were smaller, that is, they were closer to visual angle than with normal photopic viewing. This result (Table 1) is evident when comparing the angular size of the comparison

¹ Gilinsky (1951) argued that test and comparison stimuli should not be compared directly by simultaneous viewing because it tends to introduce the possibility that observers match retinal images instead of matching sizes subjectively.

disc under each viewing condition with the actual angular size (1 deg) of the test disc for each viewing distance.

Figure 1 shows size estimates for the unaided and NVG viewing conditions as a function of distance. Size estimates predicted by the law of size constancy and law of visual angle are also given. This shows that size estimates are smaller than predicted by size constancy and that the departure from size constancy is greater for NVG viewing than for the photopic viewing condition. The estimates showed greater variability at longer observation distances and for NVG viewing compared with unaided viewing, suggesting the task to be more difficult under these viewing conditions.

Table 1: Mean Disc Size Estimates with Photopic and NVG Viewing for Each Distance

Test Disc Distance (m)	Test Disc Diameter (cm) (= 1 deg)	Mean Size Estimates (Photopic)		Mean Size Estimates (NVG)	
		Diameter (cm)	Angular Diameter (deg)	Diameter (cm)	Angular Diameter (deg)
1	1.8	1.86	0.53	2.26	0.65
2	3.5	3.43	0.98	3.18	0.91
3	5.3	4.85	1.39	4.36	1.25
4	7.0	6.53	1.87	5.68	1.63
5	8.7	8.27	2.37	7.62	2.18
6	10.5	10.04	2.88	9.00	2.58

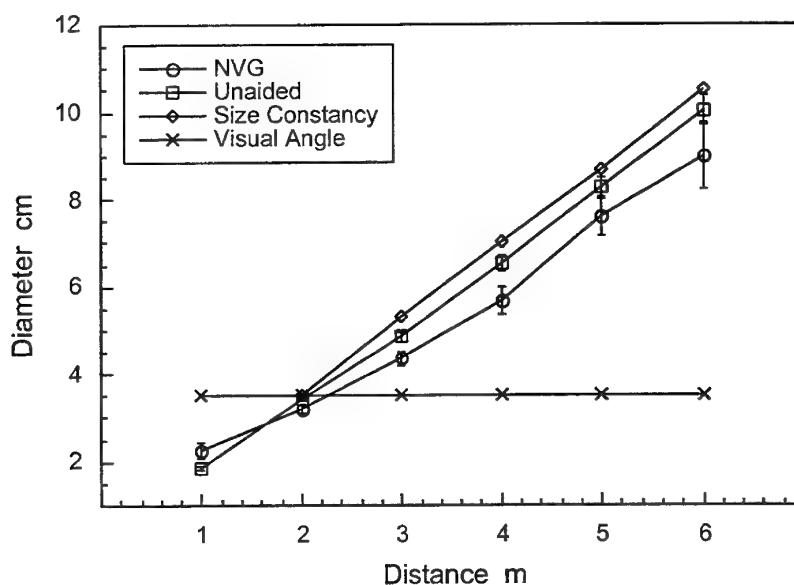


Figure 1. Mean estimates of size under two viewing conditions at six distances, with size constancy and visual angle constant presented for reference (error bars represent 1 standard error of the mean). The oblique broken line designates the locus of all data obeying the law of size constancy. The broken line parallel to the axis of abscissas is the locus of all points obeying the law of the visual angle for a 1-deg disc at 2 m.

A two-factor repeated measures Analysis of Variance (ANOVA) showed that the main effect of viewing condition was significant, $F(1, 372) = 25.1, p < 0.0001$, the main effect of observation distance was significant, $F(5, 372) = 586.7, p < 0.0001$, and the interaction between these conditions was also significant, $F(5, 372) = 4.80, p < 0.001^2$.

Post-hoc Scheffé's S tests were conducted to examine the differences between size estimates with and without NVGs at each distance. The results of these tests are given in Table 2 and show that at all distances perception of disc size viewed with the NVGs differed significantly from the disc size judged with unaided vision.

Table 2: Mean Physical Size Difference Between Unaided and NVG Viewing and 5% Critical Difference According to Scheffé's S Pairwise Comparison Test

Distance (m)	Mean Difference (m)	Critical Difference (m)	p-value
1	0.40	0.19	< .0001
2	-0.25	0.15	< .001
3	-0.49	0.24	< .0001
4	-0.85	0.40	< .0001
5	-0.65	0.56	< .05
6	-1.03	0.83	< .05

Single sample *t*-tests were used to test the significance of departure of size judgments from the law of size constancy and the law of visual angle. The *t* values and corresponding significance levels are given in Table 3. Significant departure from size constancy was found for all distances except at the 2 m distance under the normal viewing condition. This was an expected finding because the target disc and comparison disc were at the same distance for this condition. At all other distances, perceived size was judged significantly smaller than the actual size, but with the amount of underestimation larger for the NVG condition. In a similar way, significant deviations of size estimates from the law of the visual angle were found for both conditions except at 2 m in the unaided condition. Figure 2 presents a replotting of our data as the ratio of the angular size of the variable target to the angular size of the standard target. This is done to facilitate comparison of our results with those of other comparable studies (Gilinsky, 1955; Palmer and Petitt, 1977; Howard, 1996). Observers in those studies all overestimated the angular size of the target, and in Gilinsky's study, conducted outdoors, observers overestimated the angular size by nearly four times at long observation distances. Howard's (1996) results show that viewing with NVGs resulted in size estimates closer to the law of visual angle than estimates with unaided vision, but the ratio of overestimation was less than 1.5. In our study, which was conducted at shorter observation distances, the degree of overestimation at 6 m was nearly threefold.

² The probability *p* of obtaining the value *F* is small (<0.05), so the null hypothesis that there is no significant difference between conditions can be rejected.

Table 3: *t*-tests Comparing Results with Predictions According to the Law of Size Constancy and the Law of Visual Angle

Comparison	Viewing Condition	Distance (m)	<i>t</i> (31) value	<i>p</i> -value
Size Constancy	Unaided	2	-1.44	> 0.05
		3	-5.28	< 0.0001
		4	-4.36	< 0.0001
		5	-2.97	< 0.01
		6	-2.47	< 0.05
	NVG	2	-5.37	< 0.0001
		3	-11.04	< 0.0001
		4	-7.88	< 0.0001
		5	-4.36	< 0.0001
		6	-4.02	< 0.001
Visual Angle	Unaided	2	-2.47	> 0.05
		3	15.85	< 0.0001
		4	28.00	< 0.0001
		5	32.56	< 0.0001
		6	34.87	< 0.0001
	NVG	2	-5.37	< 0.0001
		3	10.16	< 0.0001
		4	12.89	< 0.0001
		5	16.62	< 0.0001
		6	14.80	< 0.0001

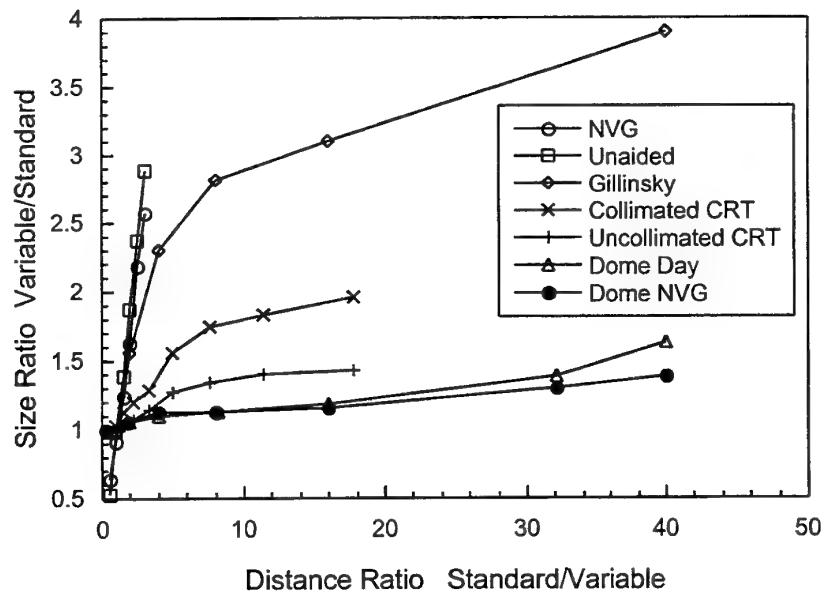


Figure 2. Size-estimate ratio of variable to standard target as a function of the distance ratio of standard to variable target for present study (NVG and photopic), the Gilinsky (1955) results [outdoor observations], the Palmer and Petitt (1977) results [collimated and un-collimated CRTs in aircraft simulator], and the Howard (1996) results [dome, dome viewing with NVGs in aircraft simulator].

5. Discussion

The primary purpose of this experiment was to investigate the perceptual task of size estimation under reduced cues for depth perception viewing with NVGs compared with unaided vision under photopic illumination levels. Second, the effect of viewing distance on size judgments was assessed. It was hypothesised that observers in the photopic viewing condition would base size estimates on the actual size of the stimuli in accordance with the law of size constancy. Observations made with NVGs were expected to depart from constancy in the direction predicted by the law of visual angle.

5.1 Size Estimation with Night Vision Goggles

The general pattern of results for both unaided vision and viewing with NVGs was closer to size constancy than visual angle, but the departure from size constancy was greater when viewing with NVGs, and more in the direction of what would be predicted by the law of visual angle. In other words, the error was greater and in the direction predicted.

The results for the normal viewing condition show that the perceived physical size (diameter) of the test disc was underestimated, but the amount of underestimation was small, never more than about 9%. Despite this slight departure from size constancy, it is clear that observers produced matches that were close to the actual size of the test discs under photopic viewing.

The results for estimates with NVGs suggest that NVGs reduced or altered some of the depth cues available compared with normal viewing, evidenced by the significant departure from the law of size constancy toward the law of visual angle observed with errors in estimates of size up to 19%. Size was misjudged even at 2 m when the distance from the test disc was the same as from the comparison disc. The only exception was the result at the shortest distance, where the perceived size of the test disc was overestimated. The standard errors of estimates at each observation distance were larger for NVG viewing than for photopic viewing at each distance, indicating that size judgments were more difficult with NVGs, and that observers were more unsure of their judgments.

Although relatively small, systematic errors in the estimation of size, together with the commonly observed underestimation of distances through NVGs, signify that vision with instruments such as NVGs is different to normal unaided vision. If NVGs do alter the way humans perceive the layout of three-dimensional space and the size of objects, then strategies that might minimise or possibly eliminate errors associated with the altered perception need to be considered.

One aspect of NVG training that might be considered is the technique described by Reising and Martin (1995) and Niall, Reising, and Martin (1997, 1999) in which observers had the opportunity to become familiar with objects at varying distances, and received verbal feedback in scaling their perceptions of the world through NVGs. Aircrew, through their training, effectively do this in a number of ways. This can be by reference to instructor pilot comments and by reference to data provided by distance and navigation sensors such as radar altimeters and distance-to-go information. In the Sikorsky S-70A-9 Black Hawk helicopter, other reference heuristics are commonly adopted. An example of this is the knowledge that the rotor disc extends to half the NVG field of view when two aircraft are separated by two rotor

diameters. There may be a need for such heuristics to be extended to more formal procedures for exposure of aircrew to different size and distance perceptions.

It should borne in mind that without further advances in technology nothing can be done to enhance the visual cues degraded by NVGs, such as resolution, noise, field of view, and monochromacy. However, an important consideration is to ensure as far as possible that as many cues for depth are available to aircrew as possible, so that the opportunity for veridical perception of the world is maximised. High illumination, high contrast, and motion parallax are cues that, if available, can help maintain veridical space perception. This may suggest selection of a flight path confined to areas that are relatively rich in cues for depth such as might be provided by vegetation and terrain features of varying height and size, and other environmental objects and structures that may serve to maintain good spatial perception. Availability of motion parallax cues will depend on the presence of objects and discrete features in the visual environment, so this cue is likely to be more useful in visually complex environments such as open woodland and urban environments, and possibly less so over expanses of water or flat desert. Motion perspective, a cue resulting from the change in angular size objects as they are approached (Braunstein, 1976), will be affected by the visibility and contrast of objects which, in the case of NVGs, is determined by illumination and reflectivity of objects. Another general source of spatial information is object familiarity, and cultural objects and structures such as vehicles and buildings on the ground can serve as "anchoring" cues for spatial perception, particularly object size.

5.2 Size and Distance Estimation

It is usually agreed that similar visual cues are involved in judging both size and distance so that any degradation in viewing conditions is likely to affect both size and distance judgments (Gibson, 1950). Although we did not measure distance estimation, it can be predicted that estimates of distance will also be adversely affected by NVG viewing. There are two bases for this. First, the perception of object size is a cue for distance, and if this is affected, then the perception of distance is also likely to be affected. If objects appear smaller, then this may suggest that they are located farther than they actually are; however, the typical error made in distance judgment with NVGs is underestimation. Hence, it is not always possible to predict the direction or the extent of such a putative effect.

Second, the cues that influence the perception of size are the same as those that influence the perception of distance. Hence, distance estimation may be more directly affected by the degradation in depth cues with NVGs, and in this case it is more difficult to predict whether distances will be over-estimated or under-estimated. In any case, the usual experimental isolation of size and distance has precluded a more ecologically valid investigation of these two related visual tasks.

5.3 Recommendations for Further Research

On the basis of outdoor studies (Gilinsky, 1955) and NVG studies at long distances (Howard, 1996), we predict that trends in our data for shorter observation distances in the laboratory would be preserved at longer distances outdoors. Reising and Martin (1995) observed that the critical distances during most demanding tasks, such as approach and landing or formation flight during night-missions, are within 45 m. It would be informative to extend the present

study to such distances. This would test judgments at distances more directly involved in flying tasks such as landing and formation flying, where correct judgment of separation is crucial.

The present study was conducted in a laboratory setting to ensure that the measurements were of high precision and the data systematic and robust in order to provide a clear indication of the nature and direction of any perceptual effects. There is now a need to extend these findings to the outdoor environment in field experimentation that would measure judgments of distance and size in a more natural, realistic environment over distances more similar to distances of operational significance.

6. Conclusion

The perceived size of objects depends on the size of the retinal image as well as proximal cues for depth. The salience of visual angle as a cue for size and distance increases when the availability of other cues is reduced. When scenes are viewed through NVGs and the availability of depth information is limited, human ability to estimate size diminishes. The results from this experiment provide evidence that limitations in depth perception associated with NVGs lead to an increased tendency for the estimates to shift away from size constancy toward the law of visual angle. This provides a clear theoretical basis for understanding the likely influence of NVGs on human spatial perception. Human ability to perceive spatial depth is an outcome of a multiplicity of overlapping cues from a given scene, and is thus a complex process. Investigation should be extended to natural settings and a wide range of distances to have a full picture of the attributes of the environment that may influence human judgments of depth.

The law of size constancy states that physical size of an object is correctly perceived irrespective of its distance from the observer or the size of the image it projects on to the retina. However, this relationship holds only when sufficient information about spatial depth is available. Some of the factors that degrade depth perception through NVGs compared to unaided vision include reduced visual acuity, contrast sensitivity, stereopsis, and field-of-view, but there are probably other factors associated with the electro-optical formation of NVG images. There is a need for systematic, quantitative experiments examining these perceptual effects. Kaiser and Foyle (1991) have stated that "...the inability to map directly from hardware characteristics to human performance necessitates careful empirical investigation of the impact of Night Vision Devices on flight critical perceptual tasks" (p. 1506). The results reported here confirm the view of Kaiser and Foyle.

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Anna Zalevski, James W. Meehan, and Philip K. Hughes

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19. ABSTRACT Human observers matched the size of a comparison disc object to the perceived size of a test disc located at between 1 and 6 m under normal daylight viewing and when viewing through night vision goggles (NVGs) under simulated starlight. The results showed that observers were more accurate at judging size with unaided vision than when viewing with NVGs. The results for unaided viewing were in accord with the law of size constancy that predicts that accurate size estimation is a result of observers taking into account the distance at which objects are located. The results for viewing with NVGs depart from size constancy and are influenced to a greater extent by the law of visual angle that predicts that size estimates are based more on the angular size of the target because there is inadequate distance information available in this condition. These results demonstrate that NVGs alter normal visual space perception and this should be taken into account in training aircrew and evaluating the effect of NVGs on flying performance. Our results are consistent with other results reported in the literature for longer observation distances.				